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DISPLACEMENT OF TETHERED HYDRO-ACOUSTIC MODEMS BY UNIFORM HORIZONTAL CURRENTS
by
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December 2009
Thesis Co-Advisors: Fotis Papoulias, Joseph Rice

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DISPLACEMENT OF TETHERED HYDRO-ACOUSTIC MODEMS BY UNIFORM HORIZONTAL CURRENTS

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Lieutenant, United States Navy
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requirements for the degree of

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ABSTRACT

Undersea sensors often include an acoustic modem buoyed above a seabed mooring or suspended beneath a surface buoy. In both cases, a vertical cable is subjected to horizontal water currents. This thesis examines the two cases, the first characterized by a cable moored to the bottom of the ocean with a buoyant end, and the second being a cable suspended or towed from a surface buoy or Unmanned Surface Vehicle (USV) with a weighted end. The equations of motion are similar, as both cases have an object affixed to the free end of the cable and the other end fixed to a stable point. A physics-based algorithm in MATLAB models the effects of drag and buoyancy on the cable and predicts the steady-state shape of the cable.

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I. INTRODUCTION

Autonomous ocean sensors serve a variety of applications, ranging from environmental monitoring to the detection of submarines. Depending on the purpose of the sensor, it may require an acoustic modem for sending data and receiving commands. A typical rigging elevates the modem above a seabed mooring or suspends it beneath a surface platform, as illustrated in Figures 1 and 2. In both cases, a cabled system is subjected to water currents, which can change the position of the cable and the attached object. The drag force may shift the modem out of a desired depth, or may even be strong enough to break the cable. For a cabled system, the effects of flow forces must be understood to predict cable behavior.

The purpose of this study is to estimate the steady-state shape of cabled modem systems in a constant and uniform horizontal flow field. A finite-element algorithm models the effects of forces acting on the cable, and predicts the expected position of the tethered object. Given a description of the mechanical system and flow velocity, a MATLAB program produces a two-dimensional plot of the expected cable position resulting from the effects of cable lift and drag.

Two case studies are examined. The first is a cable moored to the seafloor with a buoyant object at the free end (Figure 1). The second is a cable suspended from a stationary sea-surface buoy or Unmanned Surface Vehicle (USV) weighted by a dense object at the free end (Figure 2). The equations of static equilibrium are similar for both cases. Each involves a cable of some length, or scope, and an object attached to one end with the other end fixed to a stable point.

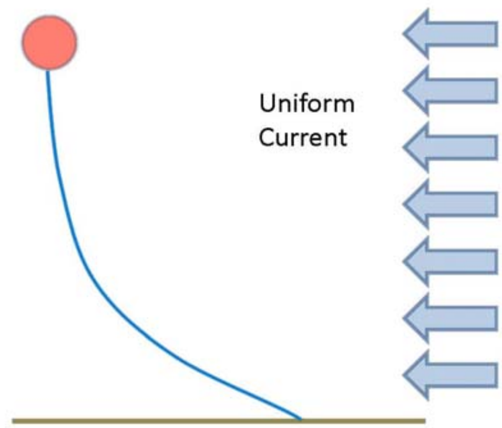

Figure 1. Simple moored cable subjected to a uniform current profile

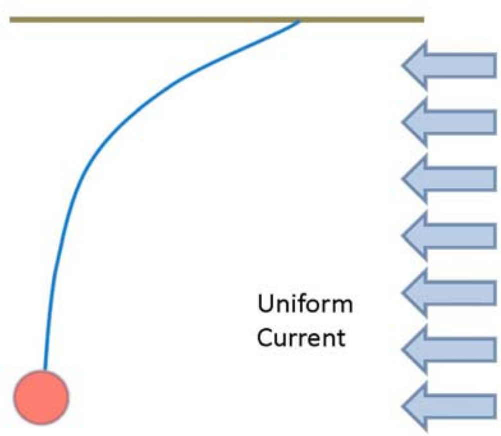

Figure 2. Simple suspended cable subjected to a uniform current profile

II. BACKGROUND

The ocean presents a challenging environment in which deployed system components are "acted upon by different forces, including gravity, tensions from the mooring lines, hydrostatic forces, and the steady and unsteady hydrodynamic forces" [1]. Examples of steady forces include the water current, or in the case of a towed array, the ship's speed. Unsteady forces may include cyclical waves where the force is constantly changing direction. The steady and unsteady forces acting on the cable determine tension, bend angle, and cable shape. This thesis develops an algorithm to estimate the cable shape resulting from steady forces imparted by a constant current.

The effect of flow forces on a cable has long been studied by engineers. Previous efforts have relied on "tables and figures" to present "hydrodynamic characteristics of moored array components such as buoys, cables, fairings, and sensors" [1]. A classic example is Pode's *Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream* [2]. Improved estimates are derived from computer programs that predict the shape of a cable under various conditions. For example, a FORTRAN program created by Carlson and Smith has been used to determine the shape and tensions of towed arrays [3].

With their theory and methods as a basis, this thesis develops a MATLAB program for predicting the steady-state shape of a moored or suspended cable subjected to constant and uniform horizontal flow.

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III. CABLE POSITION ESTIMATION THEORY

This thesis examines the two cases of a moored cable system and a suspended cable system. Displacement of the cable from vertical is a result of drag forces imposed by the horizontal flow. The equations to calculate the displacement are the same for both configurations. Both cases are characterized by a free and fixed boundary condition. The fixed boundary condition at the end of the cable is the connection to the mooring or platform. The initial forces on the free end are caused by an attached ballast or float. The moored cable has a free-moving sub-surface buoy positioned at a water depth less than the fixed end. The suspended cable has the end of the array free at a water depth greater than the fixed end.

A. FINITE–ELEMENT COMPUTATION METHOD

The finite-element method is used to estimate the displacement of a cable subject to constant flow forces. Beginning at the free end of the cable, the method takes the forces on the first element of the cable and accumulates the effective forces along the length of the cable to get the total displacement. With a constant diameter, the uniform cable can be broken into discrete cylindrical elements of equal length. The acoustic modem is treated like an additional cylindrical element of the cable, with differing dimensions (diameter, length, density).

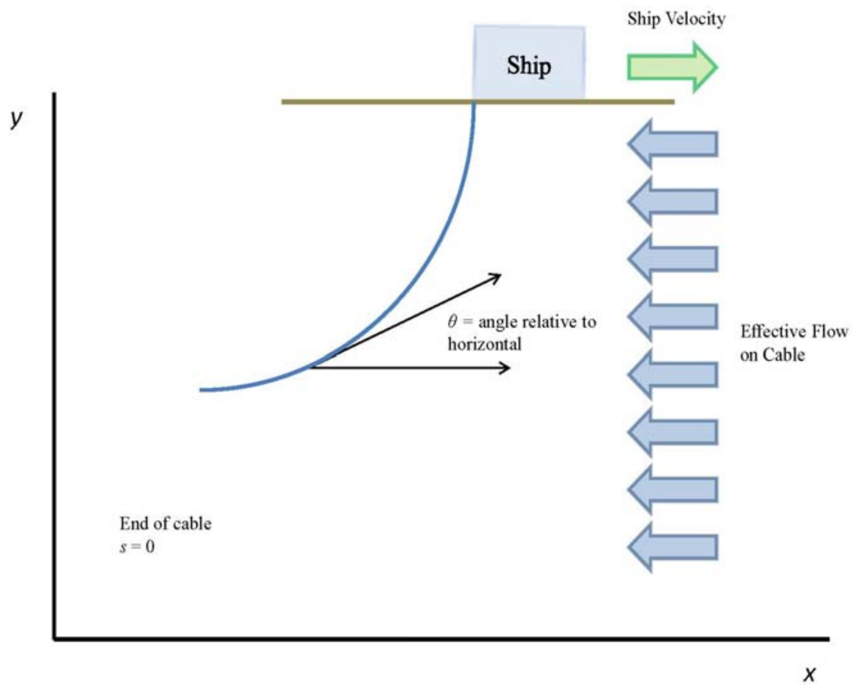

Figure 3. Drawing of towed cable system (After [3])

The formulation by Carlson and Smith, to determine the shape of a cable towed by a ship, is applicable to suspended and moored cables [3]. Figure 3 depicts a towed cable in a constant flow, with ship's velocity being equal and opposite to flow speed across the cable. In the case of the suspended cable, the ship (buoy) is stationary and the "towing effect" is caused as current flows from right to left. For the moored case, the mooring is stationary at the bottom of the ocean and the "towing effect" is likewise caused by the flow of current.

At the free end of the cable, a ballast or float maintains a rigid cylindrical modem at a prescribed depth. The initial vertical force vector on the free end of the cable is the gravitational or buoyant force caused by the displacement of the volume of the ballast or float in seawater. The initial horizontal force vector on the free end of the cable is the drag force imparted by the current on the ballast shape. The initial tension on the cable is the sum of the horizontal and vertical force vectors. Incidentally, the initial displacement angle is that of the tension vector.

The method now computes the lift, drag, and buoyancy forces for each cylindrical element of the cable, including the element associated with the modem object. For this study, the properties of the object are assumed to be those of a typical acoustic modem as given in Figure 4.

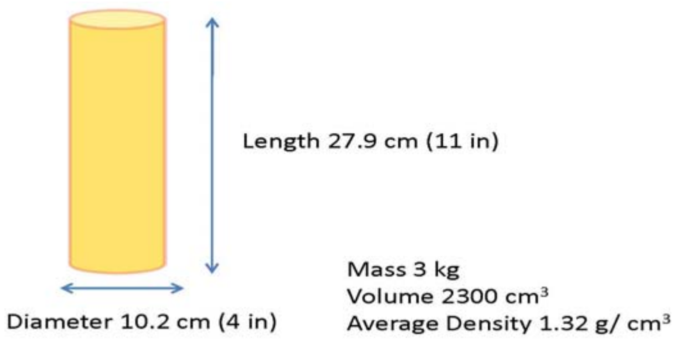

Figure 4. Cylindrical modem dimensions

For the cable and modem cylinder, the equations to find the tension, angle, vertical and horizontal displacement per unit length are the same. Equations 1–6 from Carlson and Smith [3] apply to a cylindrical shape (the shape of cable segments and modem). Equation 1 gives the tension as the sum of the vertical force vector (buoyancy and lift), the horizontal force (drag), and the cumulative vector. Equation 2 gives the change in angle, relative to the horizontal. The change in angle is then added to the previous angle (used in Equation 1) to find the tilt angle on the subsequent segment. Equations 3 and 4 give the horizontal and vertical components of tension associated with the tilt angle in the subsequent segment. A summary of forces acting on a cable section is shown in Figure 5. The effective drag and lift coefficients in Equations 5 and 6 are found by utilizing the cross-flow principle outlined in Hoerner [4], with modifications made by Carlson and Smith [3]. Equations 5 and 6 take into account the drag coefficient C_o and lift coefficient C_L and the tilt angle relative to the horizontal axis. Carlson and Smith prescribe the values of C_o = 1.1 and C_L = 0.012 from “Measurements with towed arrays and cables” [3]. These values are assumed for the cable and modem cylinders unless

otherwise noted. The drag and lift forces are then accumulated over the length of the uniform array to the fixed boundary condition. Table 1 lists the symbol definitions used in the equations.

$$\frac{d\tau}{ds} = gA(\rho - \rho_W)\sin\theta + 0.5\rho_W V^2 D(C_D \cos\theta - C_\ell \sin\theta) \tag{1}$$

$$\frac{d\theta}{ds} = \frac{1}{\tau}[gA(\rho - \rho_W)\cos\theta - 0.5\rho_W V^2 D(C_D \sin\theta + C_\ell \cos\theta)] \tag{2}$$

$$\frac{dx}{ds} = \cos\theta \tag{3}$$

$$\frac{dy}{ds} = \sin\theta \tag{4}$$

$$C_\ell(\theta) = C_o \sin^2\theta \cos\theta \,\mathrm{sign}(\theta) \tag{5}$$

$$C_D(\theta) = C_o \sin^3\theta \,\mathrm{sign}(\theta) + C_L \tag{6}$$

Table 1. Cable equations symbol definitions

Symbol	Equation Definitions and Units
g	Gravity acceleration constant (9.8 m/s^2)
A	Cross-sectional area of the cable (m^3)
ρ	Cable density (kg/m^3)
ρ_W	Seawater density (kg/m^3)
θ	Angle between the horizontal and the local tangent to the cable (deg) (Positive x axis is 0 deg)
V	Flow velocity (kt)
D	Cable diameter (m)
τ	Cable tension (N)
s	Distance along the cable (measured from the free end) (m)
ds	Cable step size (m)
C_o	Drag coefficient of a circular cylinder normal to flow
C_D	Drag coefficient of an inclined circular cylinder
F_D	Drag force (N)
C_L	Lift coefficient of a circular cylinder normal to flow
C_ℓ	Lift coefficient of an inclined circular cylinder
x	Horizontal displacement (m)
y	Vertical displacement (m)
sign(θ)	Signum Function (if θ positive, sign(θ) = 1. If θ negative, sign(θ) = – 1. If θ = 0, sign(θ) = 0.)

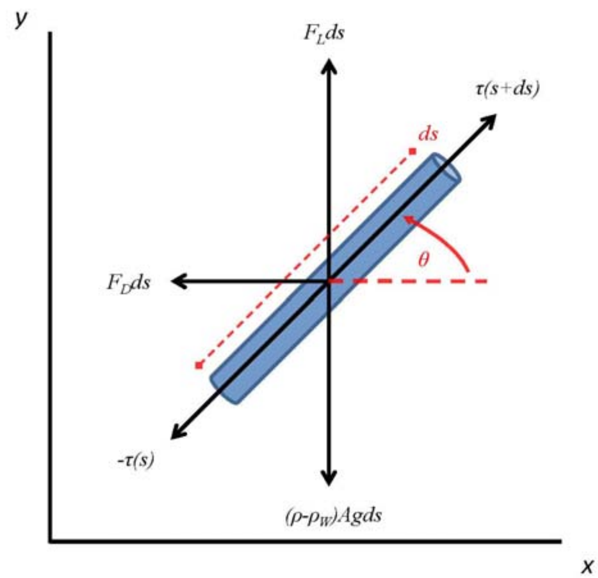

Figure 5. Forces acting on a cable segment (After [3])

At the free end of the cable, the float or ballast is composed of different materials depending on the application. If the free end is designed to suspend the modem at a depth below the surface platform, the ballast material is assumed to be corrosion-resistant Nitronic 50B stainless steel with material properties from Bauccio [5]. The density of Nitronic 50B is calculated to be 7807 kg/m^3 by adding up the individual densities from Shackelford of the component materials of Nitronic 50B (with the exception of nitogen) [6]. If the free end is designed to elevate the modem at a depth above the fixed mooring, a float made of BZ–26 syntactic foam is assumed. BZ–26 foam is made by Engineered Syntactic Systems and has properties given in Appendix B [7]. Syntactic foam retains its buoyancy properties by having minimal volume change as pressure (depth) increases. At a service depth of 2,200 m, BZ–26 has a maximum density gain of 3% over a 24-hour period [7].

The algorithm developed in this thesis allows for a spherical body, streamline body, or no body at the free end of the cable. The dimensions and material properties of the body are inputted to obtain the vertical and horizontal forces expected on the shape at a particular flow speed. The methods for finding the forces caused by each shape are similar, with differences arising from the drag coefficient C_D and cross-sectional area A.

The streamline body displays much less drag than a sphere for a given flow, fluid and volume. The sphere and streamline body shapes were chosen as these are typical shapes used as ballasts and floats. If no body is selected, the initial horizontal and vertical forces at the end of the cable can be manually inputted into the program. At the conclusion of the program, a two-dimensional (2-D) plot in the *x-y* plane renders the shape of the array. The tension and tilt angle are also calculated at each segment.

The finite-element algorithm is checked against a test case found in Pode's *Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream* [2]. Pode estimates the length of a cable required for a moored buoy to be constantly on the surface of the ocean. The buoy and cable are subject to a constant current of 5 kt in an ocean depth of 1097 m. The buoy exhibits given vertical (buoyancy and dynamic lift) and horizontal (drag) force vectors of 40500 N and 23100 N, respectively. The cable diameter D = 0.1 m and mass per unit length of 0.4 kg/m result in an estimated cable specific gravity of 4.04 in 13°C seawater (seawater density ρ_W = 1026 kg/m^3, from Kinsler et al. [8]). Pode's estimate of the required cable length is calculated to be 2670 m.

The MATLAB algorithm assumes the initial forces and cable properties (length, specific gravity) given in Pode's example to determine the shape of a 2670 m cable. By using the given normal drag force on the cable F_D = 56.9 N/m, the cable drag coefficient C_D = 1.5 is obtained from the rearrangement of Munson, et al's equation for F_D as a function of C_D

$$C_D = \frac{\rho_w V^2 A}{2F_D} \tag{7}$$

where A is the cross-sectional area of the cable of the 1 m reference segment [9].

Figure 6 shows the shape of Pode's results, while Figure 7 graphs the MATLAB result for a 2670 m long cable. For the buoy to be at the surface of a 1097 m deep water column, the MATLAB algorithm needs the cable drag coefficient to be $C_D = 1.6$. The cable shapes are similar and the estimated tilt angles relative to the horizontal at critical points are the same. For the Pode data, an angle of $\varphi_1 = 171°$ relative to the horizontal is found where the buoy cable connects to the seafloor mooring. Using the MATLAB algorithm, this angle is identical at 171°. The angle where the cable connects to the buoy is the same at $\varphi_2 = 120°$ in both cases. Note that the scale of Figure 7 is adjusted to show the similarity between the figure found in Pode's example and the algorithm results.

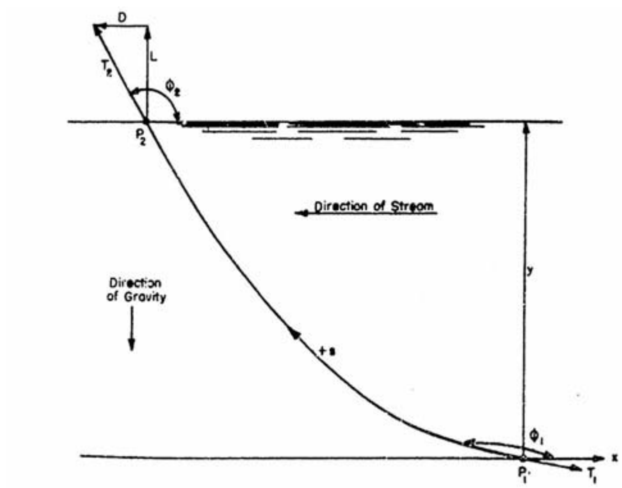

Figure 6. Drawing of Pode's example, s = 2670 m, V = 5 kt, current flows right to left (From [2])

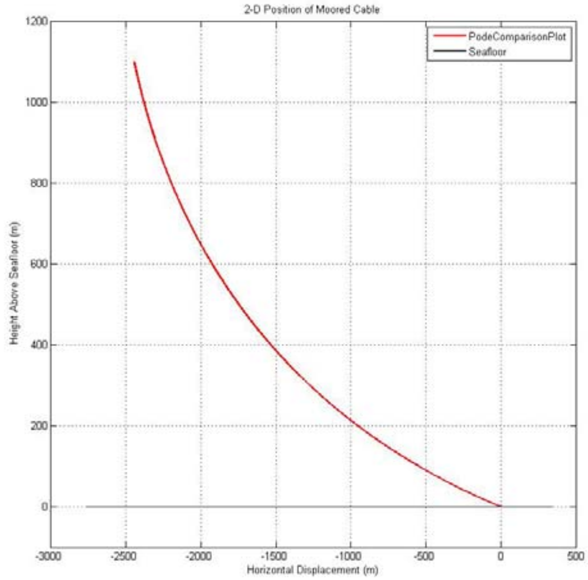

Figure 7. Algorithm results from Pode, s = 2670 m, C_D = 1.6, C_f = 0.012, V = 5 kt, current flows right to left

B. SPHERICAL BODY FLOW CHARACTERISTICS

A sphere in a horizontal flow field produces drag and buoyancy forces that govern the initial tensions on the cable. The dimensionless Reynolds number (*Re*) is first calculated to graphically determine the drag coefficient C_D, which is proportional to the horizontal drag force F_D. The vertical force is found by subtracting the buoyancy force F_B from the weight of the sphere W_{SPH} and adding the lift force F_L. *Re* is used to graphically determine the lift coefficient C_L, which is also proportional to F_L. The horizontal and vertical forces become the horizontal and vertical tension, τ_H and τ_V respectively. Table 2 lists the symbols and definitions used to the find τ_H and τ_V imparted at the end of the cable by the sphere.

Table 2. Spherical body symbol definitions

Symbol	Equation Definitions and Units
g	Gravity acceleration constant (9.8 m/s^2)
Re	Reynolds's number
V	Flow velocity (kt)
D_{SPH}	Diameter of sphere (m)
ρ_W	Seawater density (kg/m^3)
γ	Specific weight of seawater (N/m^3)
ν	Kinematic viscosity of seawater (m^2/s)
μ	Dynamic viscosity of water (N-s/m)
C_D	Drag coefficient
F_D	Drag force (N)
τ_{HI}	Initial horizontal cable tension (equivalent to F_D)
V_{SPH}	Volume of sphere = $\pi D_{SPH}{}^3/6$ (m^3)
ρ_{SPH}	Sphere material density (kg/m^3)
W_{SPH}	Weight of sphere (N)
F_B	Buoyancy force (N)
C_L	Lift coefficient
F_L	Lift force (N)
τ_{VI}	Initial vertical cable tension (equivalent to $F_B - W_{SPH} + F_L$)
τ_i	Resultant initial tension (N)
θ_i	Initial cable angle (deg)

To find Re, the formula from Munson et al. [9] is used:

$$Re = V * D / \nu \tag{8}$$

where ν = kinematic viscosity of seawater is $\nu = \mu/\rho_W$.

Assuming a temperature of 13°C, the input values for dynamic viscosity of water $\mu = 1.2*10^3$ N-s/m^2 [9] and seawater density $\rho_W = 1026$ kg/m^3 [8] are assumed. The kinematic viscosity for seawater is then found to be $\nu = 1.17*10^{-6}$ m^2/s.

The drag coefficient C_D for a sphere is found by interpolating the log-log graph in Figure 7 of experimental data of Re vs. C_D from Constantinescu and Squires [10]. Sections of the graph are estimated by the program using linear estimates of C_D from segments of Re varying from approximately 0 to $4*10^6$ (within the range of expected Re values) of the Schlichting values on Figure 8. More exact solutions from other sources correlate to Schlicthing's data and are used in the MATLAB algorithm. For example, for a Re between 0 and 1, C_D can be approximated from Stoke's law where $C_D = 24.0/Re$ [9]. Also, the C_D plateau at $5*10^3 < Re < 2.9*10^5$ is estimated to be a constant value C_D = 0.47 from examining experimental data in Hoerner [4]. A departure from the trend near "a critical Reynolds number of $Re_{CR} = 3.7*10^5$" is a steep dip that is "a manifestation of the significant differences between laminar and turbulent boundary–layer separation" [10].

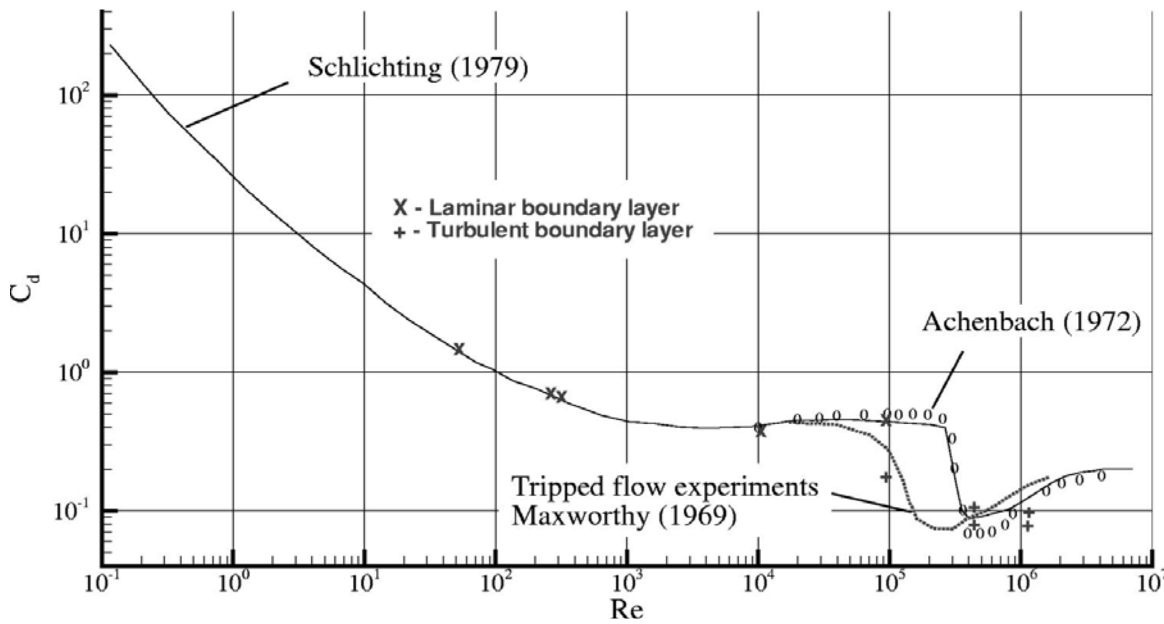

Figure 8. Experimental data showing C_D as a function of *Re* for uniform flow over a sphere (From [10])

With the approximate C_D known, the drag force F_D on the sphere is calculated by rearranging Munson, et al's equation [9] for C_D as a function of F_D,

$$F_D = \frac{1}{2}\rho_w V^2 \frac{\pi}{4} D^2 C_D \tag{9}$$

The force in the vertical direction is the buoyancy force F_B. The buoyancy force of the sphere is calculated by estimating the displacement volume of seawater [9]. The specific weight of seawater at 13°C is calculated as $\gamma = 1.01*10^4$ N/m^3 and is assumed to be constant and independent of depth.

$$F_B = \gamma(V_{SPH}) \tag{10}$$

where γ = specific weight of seawater = $\rho_w g$ (N/m^3).

Another vertical force is the lift generated by the sphere. Rearranging Munson, et al.'s equation [9], the lift force F_L depends on the C_L and is given as:

$$F_L = \frac{1}{2}\rho_w V^2 \frac{\pi}{4} D^2 C_L \tag{11}$$

However, for a sphere at rest, the C_L for Re > 1 is very small as shown by Buscaglia [12]. Since F_L linearly depends on C_L, F_L is considered to be insignificant and is neglected by the MATLAB program.

With both horizontal and vertical forces known, the tension at the free end of the cable system is calculated using the horizontal and vertical forces of the sphere. The horizontal tension τ_{HI} is the same as the drag force F_D (Equation 12). The vertical tension τ_{VI} is the weight of the sphere W_{SPH} (Equation 13) subtracted from the buoyancy force F_B (Equation 14). The resultant initial tension τ_i is calculated by taking the magnitude of the combined force vectors (Equation 15). The initial angle θ_i acting on the object is found by taking the arctangent of the vertical and horizontal forces (Equation 16).

$$\tau_{HI} = F_D \tag{12}$$

$$W_{Sph} = g\rho_{SPH}V_{SPH} \tag{13}$$

$$\tau_{VI} = F_B - W_{SPH} \tag{14}$$

$$\tau_i = \sqrt{(\tau_{HI}{}^2 + \tau_{VI}{}^2)} \tag{15}$$

$$\theta_i = \tan^{-1}(\frac{\tau_{VI}}{\tau_{HI}}) \tag{16}$$

C. STREAMLINE BODY FLOW CHARACTERISTICS

Similar to the sphere, the flow characteristics of a streamlined body produce forces that govern the initial drag and buoyancy forces on the cable. The method for computing the forces is the same with the differences arising from the values of C_D and A for a fixed volume. The values for C_D for a given fluid and speed for the streamline body are less than a sphere of comparable diameter. As a result, the streamline body has less drag than the sphere of similar volume. The dimensional inputs for the MATLAB program are the diameter of the hemispherical section (d), length of the right circular cylinder (l), and length of the conic tail section (T). The overall length of the streamline body (ℓ) is found by adding the radius of the hemisphere ($d/2$), l, and T. From experimental analysis, shown in Figure 9, the drag coefficient of the wetted surface (C_{Dwet}), and thus F_D, is a function of the ℓ/d ratio and Re. Figure 10 displays some configurations of streamline body shapes [4]. For this study, Configuration B is considered with dimensions given in Figure 11.

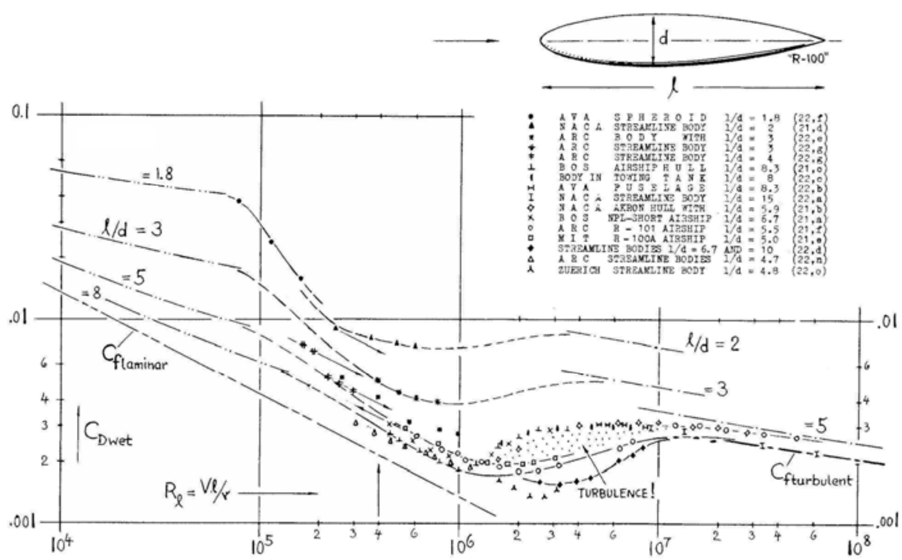

Figure 9. Selected results on the drag of rotationally-symmetric bodies (no corrections applied) (From [4])

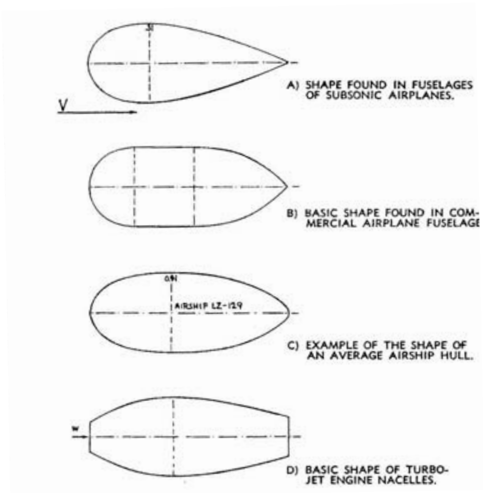

Figure 10. Some examples of basic streamline body shapes in engineering applications (From [4])

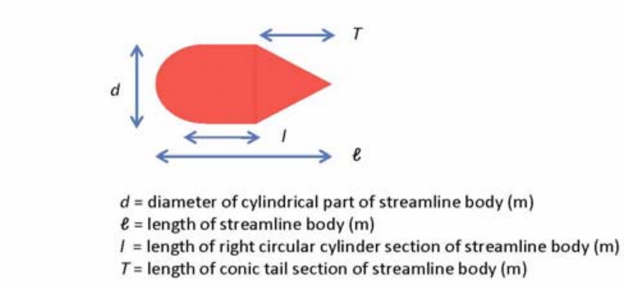

Figure 11. Dimensions used for streamline body

Table 3. Streamline body symbol definitions

Symbol	Equation Definitions and Units
g	Gravity acceleration constant (9.8 m/s^2)
Re	Reynolds number
V	Flow velocity (kt)
d	Diameter of cylindrical part of streamlined body (m)
ℓ	Length of streamline body (m)
l	Length of the right circular cylinder section of streamline body (m)
T	Length of conic tail cone section of streamline body (m)
C_{flam}	Laminar flow skin friction drag coefficient
C_f	Turbulent flow skin friction drag coefficient
C_{Dwet}	Drag coefficient for streamline body
F_D	Drag force (N)
τ_{HI}	Initial horizontal cable tension (equivalent to F_D)
V_{SB}	Volume of streamline body (m^3)
ρ_{SB}	Streamline body material density (kg/m^3)
W_{SB}	Weight of streamline body (N)
F_B	Buoyancy force (N)
C_L	Lift coefficient
F_L	Lift force (N)
τ_{VI}	Initial vertical cable tension (equivalent to $F_B – W_{SPH} + F_L$)
τ_i	Resultant initial tension (N)
θ_i	Initial cable angle (deg)

The method for finding the drag forces and buoyancy forces is the same as that of the sphere. The *Re* of the streamline body is obtained from Equation 8 except that *d*, the diameter of the cylindrical section, is substituted for *D*. With *Re* known, the drag coefficient for the streamline body C_{Dwet} is found. Figure 13 displays the values for C_{Dwet} relating to *Re* for a streamline body [4]. The program models C_{Dwet} as a function of *Re* in two conditions: $Re < 10^5$ and $Re \geq 10^5$. It is assumed that the streamline body shown in Figure 12 follows the same as those of Configuration B with the same length/diameter ratios.

For *Re* of $10^4 < Re < 10^5$, the flow is laminar. The Blasius solution for C_{flam} (laminar skin-friction coefficient) for flow over a flat plate characterizes the drag. To account for the size of the streamline body, C_{Dwet} is a function of C_{flam} and the diameter-to-length ratio (d/ℓ). Note that for an extremely large d/ℓ, the streamline body resembles a flat plate and $C_{Dwet} = C_{flam}$. For $Re<10^4$, the MATLAB program assumes that the C_{Dwet} follows the Blasius solution for laminar flow.

Blasius solution for flow over a flat plate for low *Re* [9] gives

$$C_{flam} = \frac{1.328}{\sqrt{Re}} \tag{17}$$

The drag coefficient for streamline body with laminar flow [4] is

$$C_{dwet} = C_{flam}[1+(\frac{d}{\ell})^{\frac{3}{2}}] + 0.11(\frac{d}{\ell})^2 \tag{18}$$

At higher *Re* ($10^5 < Re < 10^{10}$), the flow is turbulent. Hoerner uses data from the experimental data from the Schoenherr line for flow over a surface (Figure 12) to compute Equation 19 for the skin-friction drag coefficient C_f. To account for the effect of streamline body dimensions, Hoerner developed Equation 20 to find C_{Dwet} using experimental data in Figure 13 turbulent flow over a streamline body.

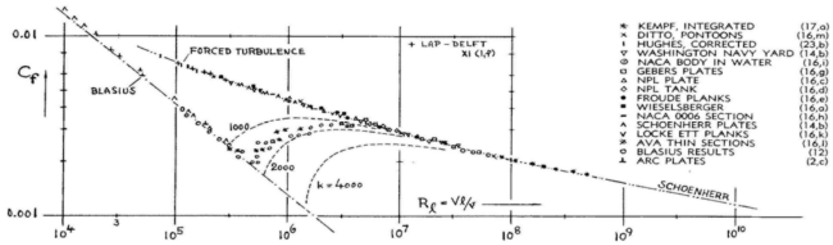

Figure 12. Average or total skin-friction drag coefficient of smooth and plane surfaces (in incompressible flow) in air and in water (From [4])

The turbulent skin-friction drag coefficient using the Schoenherr line is approximated by

$$C_f = \frac{1}{[3.46\log(Re) - 5.6]^2} \tag{19}$$

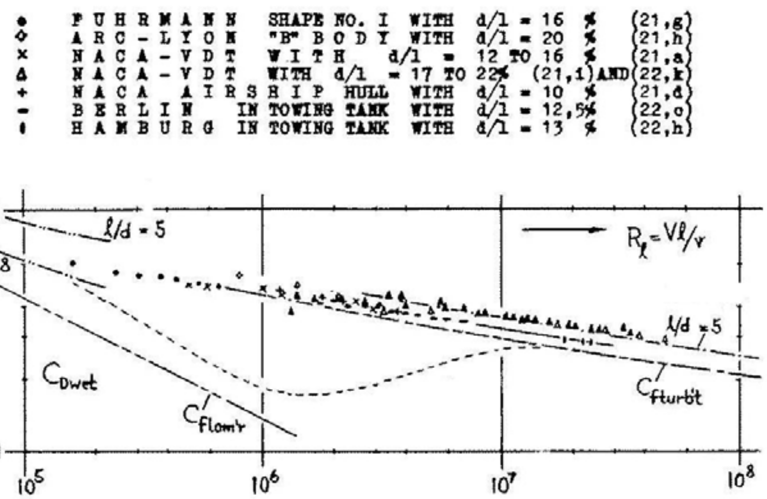

Figure 13. Drag of streamline bodies, tested in turbulent wind tunnels or with turbulence simulation (From [4])

The drag coefficient for a streamline body with turbulent flow is

$$C_{Dwet} = C_f[1 + 1.5(\frac{d}{\ell})^{\frac{3}{2}} + 7(\frac{d}{\ell})^3] \tag{20}$$

As with the sphere, C_{Dwet} is found and inputted into Equation 9 to calculate F_D. The buoyant force is found from Equation 10 except now the volume is that of the streamline body using Equation 21.

V_{SB} = volume of hemisphere + volume of right circular cylinder + volume of cone

$$V_{SB} = \frac{\pi}{6} d^3 + \frac{\pi}{4} d^2 L + \frac{\pi}{12} d^2 T \tag{21}$$

For simplicity, the length of the tail cone T is set to be the same as the diameter of the cylinder d. F_L is assumed to be negligible since the streamline body is assumed to have uniform pressure (hydrostatic) at all points around the body and a zero angle of attack (no lift is generated). The tension τ_i and angle θ_i on the modem produced by the streamline body is calculated with Equations 15 and 16.

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IV. CASE STUDY–THE MOORED CABLE

The first case study is a modem moored in the deep ocean. The ocean depth is assumed to be 3000 m. The desired depth of the modem is 1000 m with the cable being approximately 2000 m long (see Figure 14).

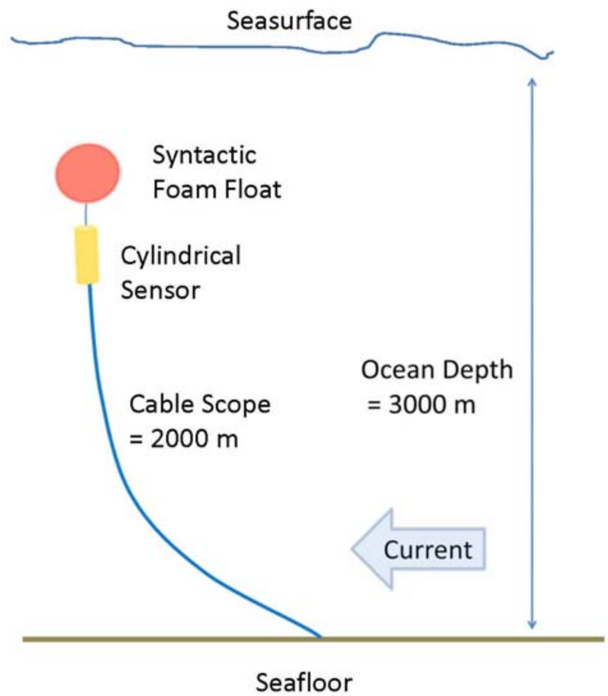

Figure 14. Moored case study with spherical float

BZ–26 syntactic foam is used as flotation material. The cable is chiefly comprised of Nitronic 50B Stainless Steel and has a net diameter of 16 mm (5/8 in). The cable is typically made of many strands of material braided into a cylindrical shape, and the net diameter is the diameter of all the strands combined. It is expected that the net Yield Strength (σ_{YS}) of the cable is greater than that of a solid material's σ_{YS} with the individual strands acting together. However, the σ_{YS} assumed in these case studies is that of the solid material itself to represent a lower bound for material failure. It is assumed the cable is fabricated in such a way that it is flexible and supports a wide range of bend angles. At this diameter, with a σ_{YS} of 380 MPa for Nitronic 50B, the maximum allowable tension in the cable (τ_{max}) is 75.2 kN before plastic deformation.

$$\tau_{\max} = \pi(\frac{D}{2})^2 \sigma_{YS} \qquad (22)$$

The determination of the appropriate step size *ds* for the finite-element representation is important to accurately estimate array position. As the step size decreases, the algorithm conducts more calculations and requires more computation time. There is a point of diminishing returns at which the step size is small enough that using a smaller step size does not appreciably improve the results. The minimum step size that can be used with this MATLAB program is *ds* = 1 m. To find the most efficient step size, the case of a 2.4 m diameter spherical float in a current of 3 kt is presented. Using BZ–26 syntactic foam, the buoyancy force is 72.8 kN. The catenary is plotted for step sizes of 100, 10, and 1 m. Figure 15 shows that at a step size of *ds* = 1 m the catenary has converged. Therefore, for the remaining analysis for the 2000 m cable uses step size *ds* = 1 m.

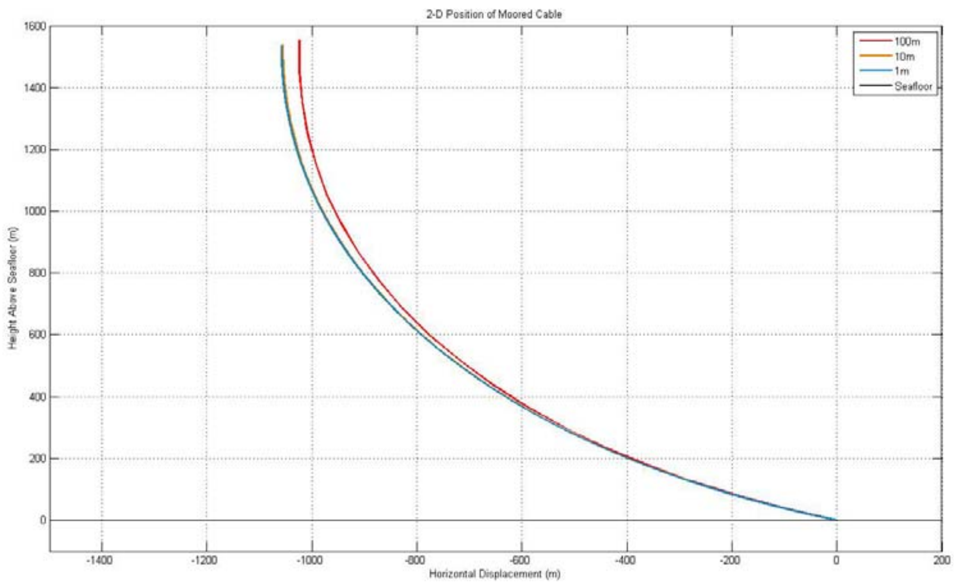

Figure 15. Step size variations for 2.4 m diameter spherical float, Nitronic 50B cable, *D* = 16 mm, *s* = 2000 m, *V* = 3 kt, current flows right to left

The volume of the flotation material relative to the cable properties impacts the vertical displacement. For a given cable length, if the buoyancy force is not large enough, the weight of the cable can sink the modem below the desired operating depth. The weight of a 2000 m, 16 mm diameter Nitronic 50B cable is 3090, thus requiring a large buoyancy force to suspend the cable. The algorithm indicates that the vertical forces at the end of the cable are inadequate when the cable crosses the imaginary seafloor boundary. This is shown in Figure 16 when the cables associated with spherical diameters of 2.1 and 2.0 m intersect the seafloor. Although such interaction with the ground would change the forces acting on the cable, the computations in this algorithm do not account for the seafloor.

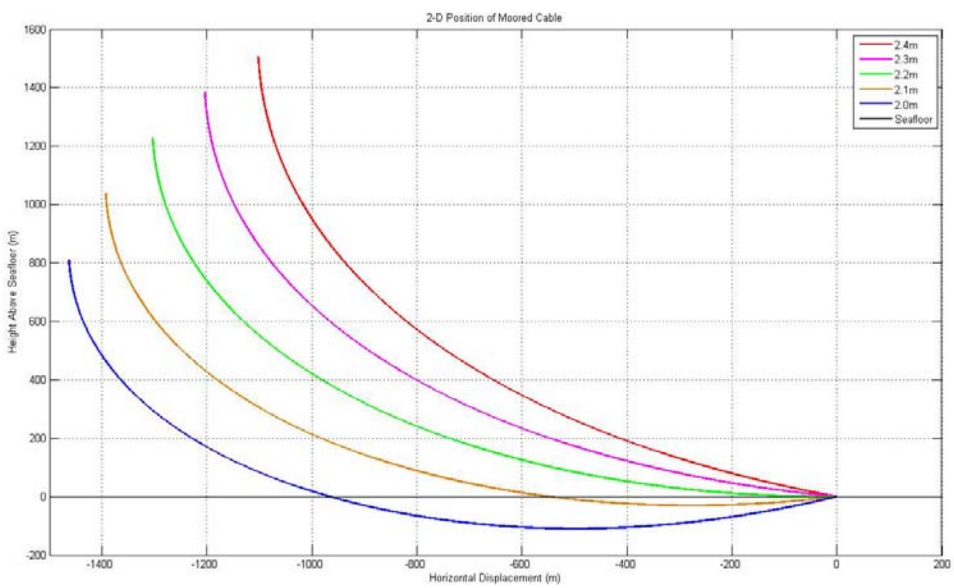

Figure 16. Spherical float diameter variations, Nitronic 50B cable, D = 16 mm, s = 2000 m, V = 3 kt, current flows right to left

The shape of the float strongly influences the amount of horizontal drag F_D imposed on the end of the array. The sphere has a higher C_D and a higher cross-sectional area than the streamline body of the same volume. The volume is chosen to elevate the modem at a prescribed depth across a given current range. For this case study, to get the same buoyancy force as a 2.3 m diameter spherical float, a streamline body with 1.07 m diameter and 6.96 m length is specified. With a current of 3 kt, the sphere C_D is 0.232 and the streamline body C_D is 0.004. The F_D on the sphere is 1.28 kN and on the streamline body is 9.6 N. Figure 17 compares the cable shapes produced by the sphere and streamline body. Note that with less drag force on the streamline body, the horizontal position of the array changes less over the depth range and also the maximum tension on the cable is less with τ_{Sphere} = 45.2 kN and τ_{SB} = 45.1 kN. Both tensions are less than τ_{max} by nearly a factor of 1.6. Note that the shapes of the cable for each shape are similar. For such a long length, the drag and lift forces acting on the cable dominate the cable displacement.

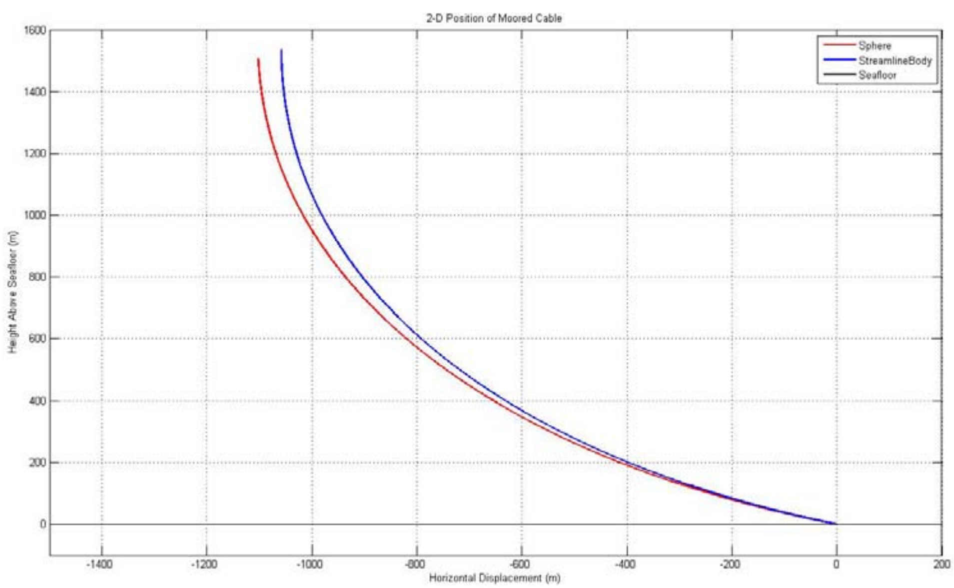

Figure 17. Comparison of sphere vs. streamline body float, Nitronic 50B cable, D = 16 mm, s = 2000 m, V = 3 kt, current flows right to left

For further analysis, the streamline body is chosen. As the current is increased from 0 to 3 kt, the shape of the cable catenary changes dramatically. At low speeds, the cable is nearly vertical. As current speed increases, F_D increases to cause more horizontal displacement resulting in a modem depth deeper than the desired 1000 m. Figure 18 shows cable shape for the array for a streamline body with diameter d = 1.07 m diameter and length ℓ = 6.96 m.

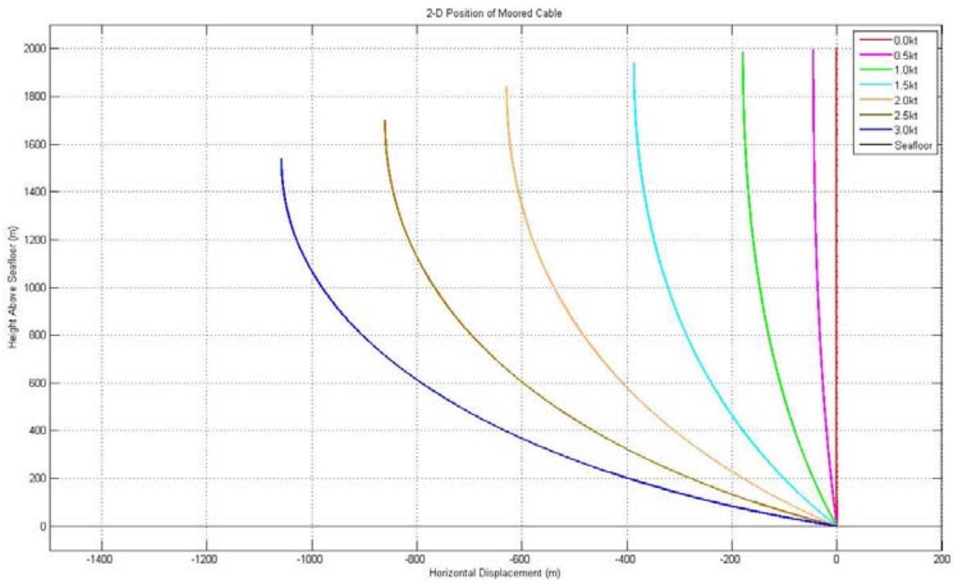

Figure 18. Comparison of cable shapes with streamline body float, Nitronic 50B cable, V varies 0–3 kt, D = 16 mm, s = 2000 m, current flows right to left

The cable material is varied when a "high-strength, light weight polyethylene fiber" is substituted for Nitronic 50B [12]. Honeywell's Spectra fiber 1000, whose properties are in Appendix C, has a high resistance to chemicals, water, ultraviolet light and flexural fatigue. The product has good resistance to abrasion and is used in marine applications such as marine lines as well as fishing lines and commercial fishing nets. The product density is 970 kg/m^3, resulting in a specific gravity of 0.95 in 13°C seawater. For comparison of the effects of a lighter material on cable shape, a 2000-m 15.88-mm diameter Spectra 1000 (1300 denier) line is modeled against a 16-mm diameter Nitronic 50B cable at 3 kt. The maximum tension found in the Spectra 1000 line is 45.4 kN while τ_{max} (based on the products' Ultimate Tensile Strength of 3.00 GPa) is 594kN. As expected, the buoyant Spectra has less downward vertical displacement than the heavier Nitronic 50B.

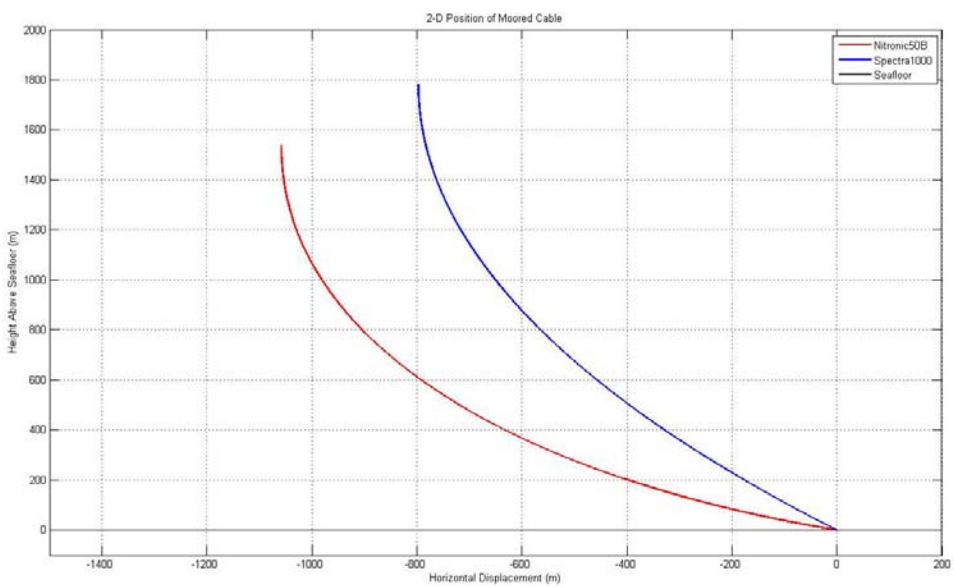

Figure 19. Comparison of Nitronic 50B vs. Spectra 1000 cables with streamline body float, D = 16 mm, s = 2000 m, V = 3 kt, current flows right to left

The diameter of the cable can also be adjusted to find the minimum cable diameter before cable failure. The cable diameter in Figure 20 were varied to find when breakage would occur. By only changing the cable diameter D, it was found that the cable size could be reduced to 12.7 mm (1/2 in). The maximum tension found in the cable of 45.3 kN nearly exceeds the calculated τ_{max} of 48.1 kN.

The smaller cable diameter produces less cable drag thus less horizontal force, resulting in a more vertical cable. The tradeoff with reduced cable diameter is that there is less material and inherently less allowable strength. Since this is a steady-state analysis, snap loads should be considered when actually specifying the cable dimensions.

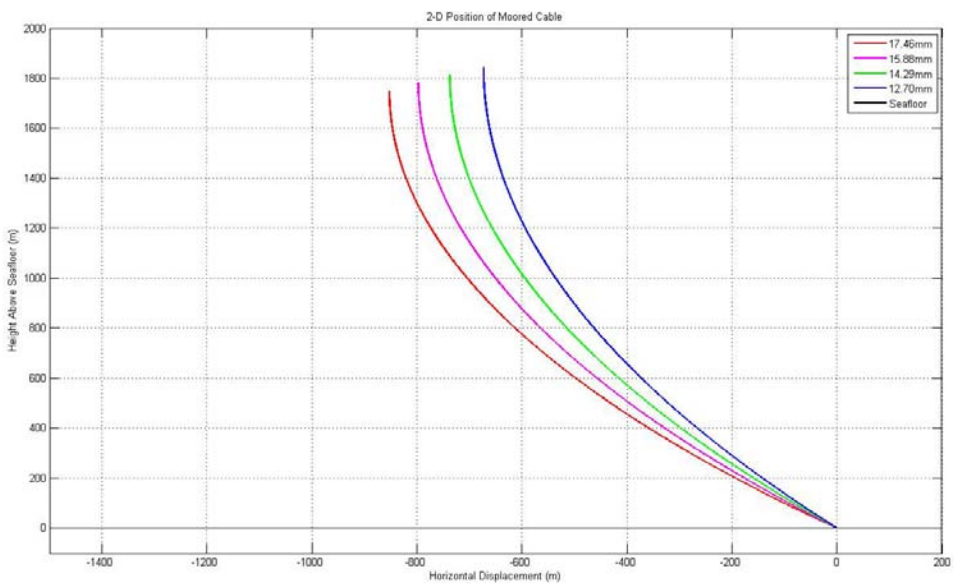

Figure 20. Comparison of Spectra 1000 cable with varying cable diameter *D*, streamline body float, *s* = 2000 m, *V* = 3 kt, current flows right to left

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V. CASE STUDY–THE TOWED CABLE

The second case study is an acoustic modem suspended from a surface buoy in the ocean. The desired depth of the modem is 30 m with the cable scope being approximately 30 m. The cable is chiefly comprised of Nitronic 50B stainless steel with an enclosed electrical connection between the buoy and the modem. The cable has a net diameter of 6.4 mm (1/4 in). At this diameter, the maximum allowable tension in the cable is found to be τ_{max} = 12.0 kN (using Equation 22). The same assumptions as with the cable in the moored case study are made here.

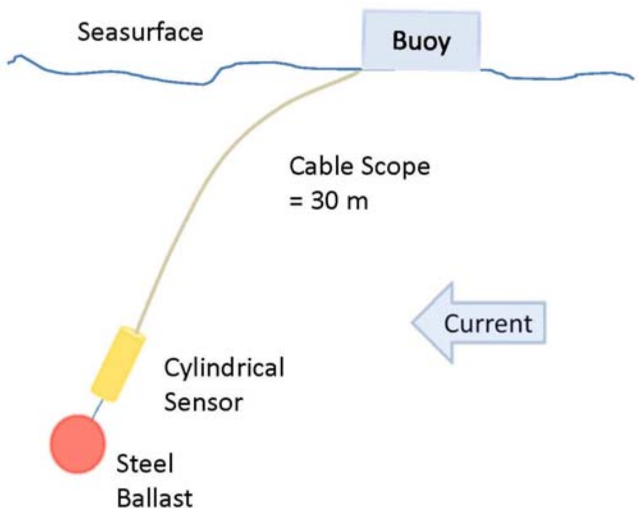

Figure 21. Towed case study with spherical ballast

The same analysis done with the moored cable can be performed on the towed cable. First, the most appropriate step size *ds* for the finite-element algorithm is found by parametric analysis shown in Figure 22. Convergence of cable shape occurs with step size *ds* = 0.1 m. For the remainder of this case study analysis, a step size of *ds* = 0.1 m is used.

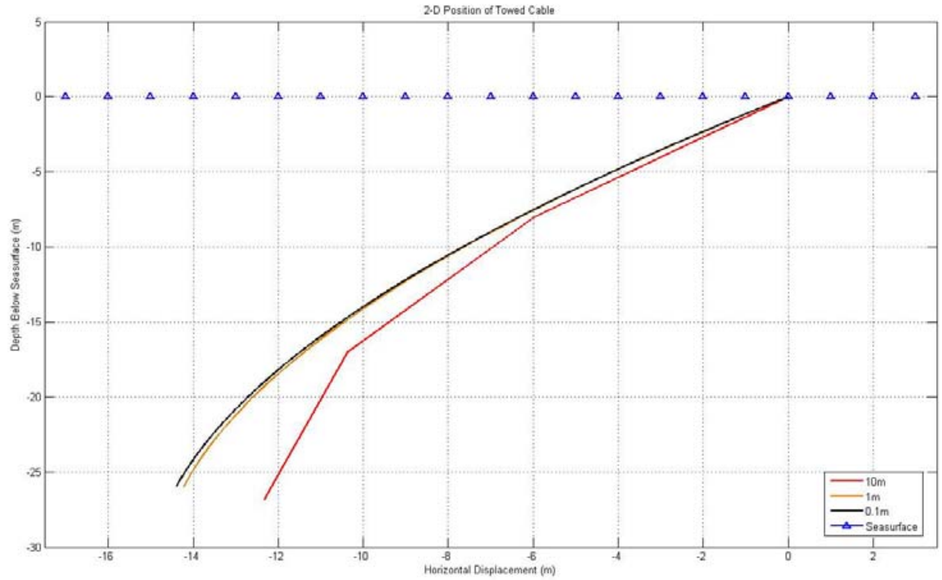

Figure 22. Step size variations for a 0.2 m diameter spherical ballast, Nitronic 50B cable, D = 6.4 mm, s = 30 m, V = 3 kt, current flows right to left

The size of the ballast material relative to the cable impacts the vertical displacement. A larger ballast of similar material pulls the pulls the end of the cable down more. If the ballast is too small, it may not be enough to maintain the modem at the desired depth. The algorithm indicates that the vertical forces at the end of the cable are inadequate when the cable crosses the imaginary seasurface boundary. When the cable is light, and the size of the ballast is very small, the cable will appear to be above the sea surface. Although the cable cannot actually breach the upper boundary of the sea surface, the MATLAB algorithm does not recognize a boundary violation.

As previously determined, the sphere has a higher C_D and A than the streamlined body. A 0.2 m diameter spherical ballast has the same weighting characteristics as a streamline body of 0.09 m diameter and 0.58 m length. For a current of 3 kt, the drag coefficient of the sphere is $C_D = 0.47$ and drag force is $F_D = 18.0$ N. The streamline body values are $C_D = 0.008$ and $F_D = 0.12$ N. Figure 23 compares the cable shape arising from a sphere and streamline body. Again, with less drag on the streamline body, the horizontal displacement of the cable is less. The maximum tension on the cable is nearly the same with $\tau_{Sphere} = 341$ N and $\tau_{SB} = 342$ N. These tensions are less than τ_{max}.

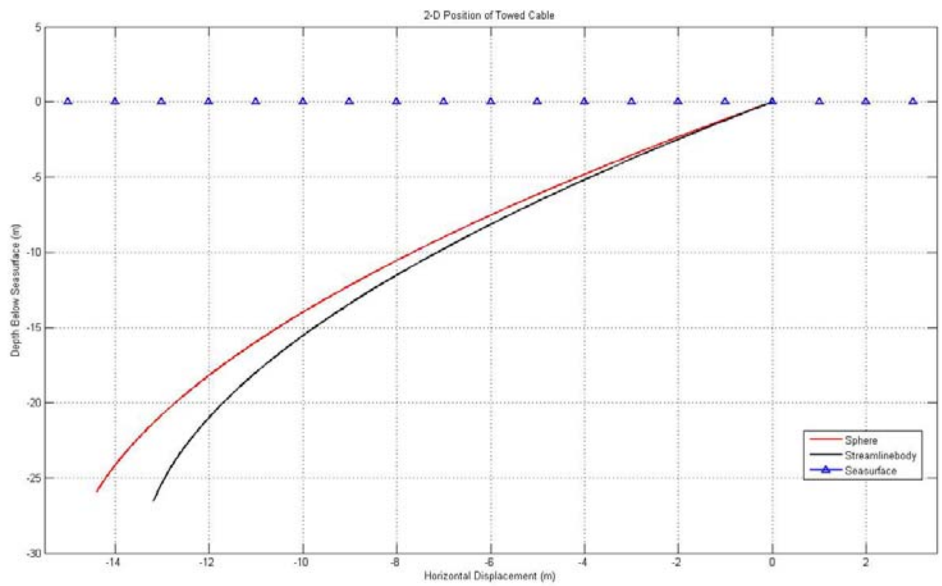

Figure 23. Comparison of sphere vs. streamline body ballast, Nitronic 50B cable, $D = 6.4$ mm, $s = 30$ m, $V = 3$ kt, current flows right to left

The streamline body ballasted cable shape is predicted for currents of 0 to 3 kt. The cable behavior is similar to the moored cable where at lower speeds, the cable is nearly vertical and at higher speeds, depth decreases while horizontal displacement increases. Figure 24 shows the shape of the cable for a streamline body with d = 0.09 m and ℓ = 0.58 m.

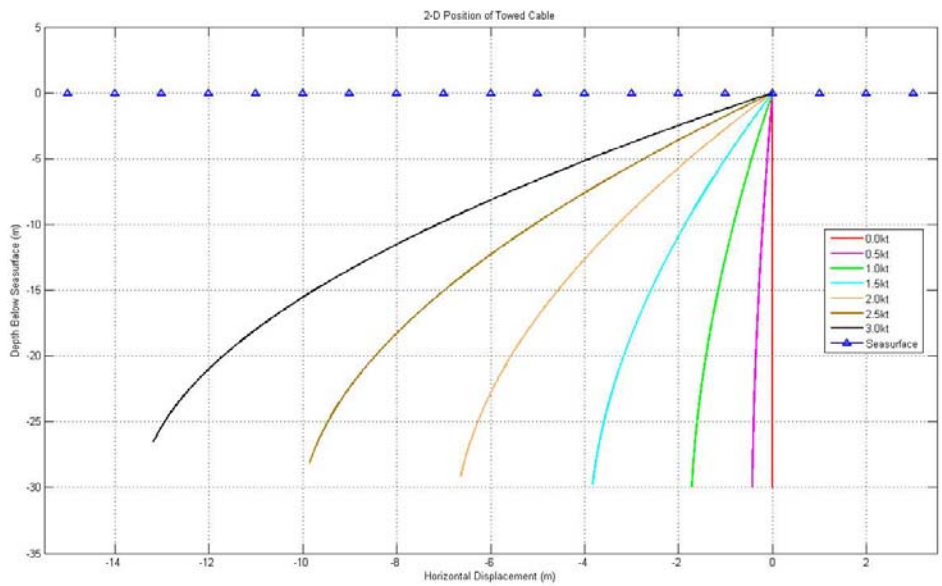

Figure 24. Comparison of cable shapes of streamline body ballast as V varies 0–3 kt, D = 6.4 mm, s = 30 m, current flows right to left

In Figure 25, Spectra 1000 is substituted for Nitronic 50B using the streamline body. With the lighter Spectra 1000, the cable is less vertical as the buoyancy forces act in an upward direction. For the given cable diameter D = 6.4 mm, the maximum allowable tension in the cable with the Spectra 1000 is found to be 95.0 kN, compared to 12.0 kN with the Nitronic 50B. The analysis for the minimum diameter cable needed under these conditions can also be done.

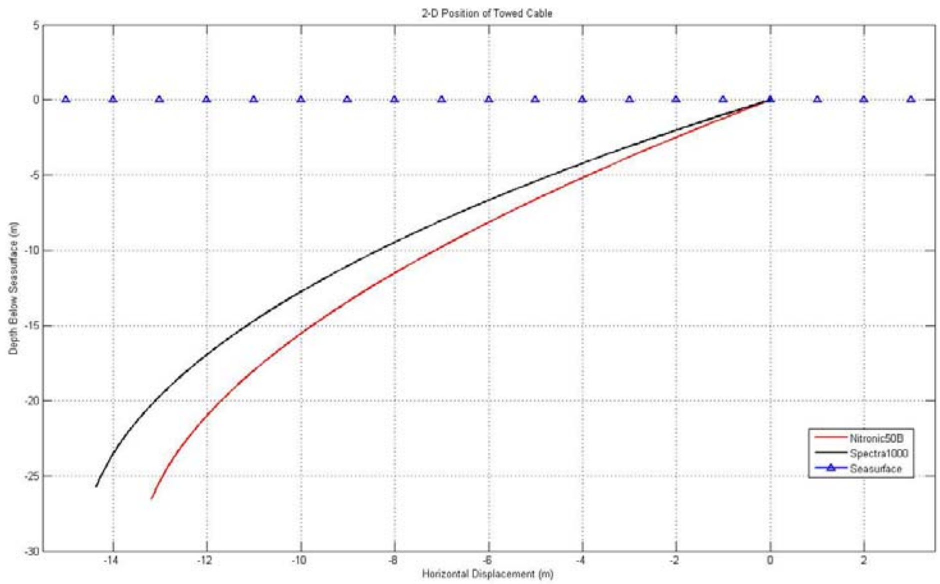

Figure 25. Comparison of Nitronic 50B vs. Spectra 1000 cables with streamline body ballast, D = 6.4 mm, s = 30 m, V = 3 kt, current flows right to left

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VI. CONCLUSIONS

A horizontal current acting on a vertical cable imparts a drag force that displaces the cable. To find the overall cable shape, first the tension and initial angle imparted by the vertical and horizontal forces acting on the ballast/float shape are found. With the initial conditions known, the drag and lift acting on the cylindrical modem and uniform cable are found and accumulated over the length of the array to the fixed point. With the array tensions and angles known, the cable shape is determined.

Depending on the length of the array, the ballast/float shape may or may not significantly influence the array shape. A streamline body compared to a sphere of equal volume has less initial drag force. However, when the cable is very long (as in the 2000-m case) the position of the array is more dependent on drag of the cable. At a shorter cable scope, the forces on the float/ballast body are more dominant. In either case, it is recommended that a streamline body shape be used as the initial drag forces are less.

Design of a tethered modem requires knowing the desired operational requirements of the system. The system tolerances dictate the cable and ballast/float material type and size and the designer should understand the trade-offs. For example, while a larger float shape may add buoyancy, the additional drag may actually move it farther from the desired position. Using this MATLAB algorithm, the designer can analyze these factors and specify a design to meet the operational requirements.

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[12] Honeywell Spectra Fiber 1000 Product Information Sheet (2008), http://www51.honeywell.com/sm/afc/common/documents/3.1_SpectraFiber1000.pdf (accessed September 2, 2009).

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APPENDIX A. MATLAB CODE

```
% CABLE ESTIMATOR is a program to compute the initial value problem for a
% first order system of differential equations describing the shape of an
% array system. The array can either be towed or moored on the bottom of
% the ocean and has a cylindrical acoustic modem attached at the end. The
% program allows the user to consider two types of ballast or float shapes
% attached at the end of the modem - a sphere or streamline body. The user
% can also input in arbitrary initial tensions for towed or moored cases.
% The program allows the user to change the material properties and
% dimensions of the cable. The outputs of the program are tension, the
% angle relative to the horizontal, and x, y position on a two-dimensional plot.

% Symbol Definitions
% A = cross-sectional area of cable at a point (m^2)
% DENC = cable density (kg/m^3)
% DENW = water density (kg/m^3)
% thetadeg = the angle between the horizontal and local tangent at a point
% on the cable (deg) (positive x axis is 0 deg)
% V = towing velocity (or current) (kt)
% DC = diameter of cable (m)
% tauN = cable tension (N)
% s = cable length (m; s = 0 is end of array)
% Co = basic drag coefficient
% Cf = drag/lift coefficient correction factor (Cf = pi * Cp; Cp is the
% classical drag coefficient; See Hoerner pg. 3-11 "Cross-Flow Principle")
% Cl = corrected lift coefficient
% Cd = corrected drag coefficient
% g = gravity acceleration constant (m/s^2)
% 1 m = 3.2808 ft = 39.37 in
% 1 kg = 2.2046 lb
% 1 lbf = 4.45 N

clear all

%Program Inputs
V = 3.0; %knots

Shape = 2; % Shape = 1 => Sphere, Shape = 2 => Streamline body,
% Shape = 3 => No attached body or sensor (towed cable),
% Shape = 4 => No attached body or sensor (moored cable)
% If Shape = 3 or 4, input THI and TVI on lines 283/284 for arbitrary
% initial horizontal and vertical forces.
```

```
DSph = 2.3; % Diameter of sphere (m)
% Float 2.3 m
% Ballast 0.2 m

DSB = 1.071091; % Maximum diameter of streamline body (m)
% Float 1.071091 m (Vol 2.3 m sphere)
% Ballast 0.08933 m (Vol 0.2 m sphere)

LSB = 6.962093; % Length of cylindrical part of streamline body (m)
% Float 6.962093 m (Vol 2.3 m sphere)
% Ballast 0.58069 m (Vol 0.2 m sphere)

TSB = 1.071091; % Length of conical section (tail) of streamline body (m)
% Float 1.071091 m (Vol 2.3 m sphere)
% Ballast 0.08933 m (Vol 0.2 m sphere)

Density = 1; % Density of the shape, DEN = 1 => DENF (float),
% DEN = 2 => DENB (ballast)

L = 2000; % Cable length (m) Pode example 2760 m

DC = 0.015875; % Cable diameter (m) Moored 0.015875 Towed 0.00635 Pode
0.0111125

ds = 1; % Step interval (m) limit is 0.1

SGC = 0.95; % Specific gravity of cable in sw
% Nitronic 50B 7.6096 Pode 4.04 Spectra1000 0.95

% Common Terms
g = 9.80665; % m/s^2;
V = 0.51444 * V; % Conversion from knots to m/s
DENB = 7807.4; % Density of Nitronic 50B (kg/m^3) for ballast material (Calculated)
DENF = 390; % Density of BZ-26 foam (kg/m^3) for float material (Spec Sheet)
DENW = 1026; % Density of seawater @ 13C kg/m^3 (KFCS)
Dyna = 1.17 * 10^-3; % Dynamic viscosity for water, "u" (mu), Ns/m^2,
% water @ 13C, Munson p.759)
Kine = Dyna / DENW; % Kinematic viscosity for seawater , "v" (nu), m^2/s,
% Munson p.19) (for sw 1.1404e-006)
gammasw = DENW * g; % Specific weight of seawater at 13C, N/m^3, assume
% constant and independent of depth (see Munson example, p.71)
YS = 380*10^6; % Yield strength
% Nitronic 50B stainless steel 380 MPa
% Spectra 1000 3000 MPa (Use ultimate tensile strength as approximation)
MaxCTau = pi * (DC/2)^2 * YS;
```

```
if Density == 1
   DEN = DENF;

else if Density == 2
   DEN = DENB;

   end
end

% Uniform cable parameters
DENC = SGC * DENW; % Density of cable (kg/m^3)
Co = 1.1; % Value of Co = 1.1 from Carlson and Smith (p.3)
% From experimental measurements. To match Pode example, Co is about 1.6.
Cf = 0.012; % Value of Co = 0.012 from Carlson and Smith (p.3)
n = L/ds; % Number of steps to calculate cable parameters

% Cylindrical sensor modem and weight/float are used to calculate the
% initial tension at the end of the cable

% Cylindrical acoustic modem dimensions. These values remain constant.
DS = 0.1016; % Nominal acosutic modem diameter (m) (4 in)
LS = 0.2794; % Nominal acoustic modem length (m) (11 in)
VOLS = pi * DS^2 * LS / 4; % Volume (m^3)
MS = 3; % Mass of acoustic modem in air (kg)
DENS = MS / VOLS; % Acoustic modem density (kg/m^3)
AS = pi * DS * DS / 4; % Cross-sectional area of acoustic modem
CoS = 1.1; % Same value as cable
CfS = 0.012; % Same value as cable

% Initial veritcal and horizontal tension acting on the acosutic modem are
% found by calculating the drag force (horizontal) and buoyancy force
% (vertical)caused by the ballast/float.

% Assume that the ballast/float shapes cause negligible lift.
% Assume the distance between the ballast/float and modem is negligible.

if Shape == 1 % Sphere
   ReSph = V * DSph / Kine; % Renoylds number for sphere

   % Approximations of Cd for a sphere given the expected Renyolds
   % number with problem parameters from Constantinescu and Squires p.2
   % (Schlichting) and Hoerner p.3-8.

   if ReSph>=0 && ReSph<1
```

```
   CdSph = 24.0/ReSph;
end
% Low Re approximation (Munson p.524) (Stoke's Law)

if ReSph>=1 && ReSph<4
   CdSph = -5.3333 * ReSph + 29.3333;
end

if ReSph>=4 && ReSph<10^1
   CdSph = -0.5833 * ReSph + 10.333;
end

if  ReSph>=10^1 && ReSph<5*10^1
   CdSph = -0.075 * ReSph + 5.25;
end

if ReSph>=5*10^1 && ReSph<3*10^2
   CdSph = -1.6*10^-3 * ReSph + 0.52;
end

if ReSph>=3*10^2 && ReSph<2*10^3
   CdSph = -1.4*10^-4 * ReSph + 0.745;
end

if ReSph>=2*10^3 && ReSph<2.9*10^5
   CdSph = 0.47;
end
% Plateau estimation (Hoerner p.3-8)

if ReSph>=2.9*10^5 && ReSph<3.7*10^5
   CdSph = -4.75*10^-6 * ReSph + 1.8475;
end

if ReSph>=3.7*10^5 && ReSph<7*10^5
   CdSph = 2.3256*10^-8 * ReSph + 0.0814;
end

if ReSph>=7*10^5 && ReSph<2*10^6
   CdSph = 7.6923*10^-8 * ReSph + 0.04615;
end

if ReSph>=2*10^6 && ReSph<4*10^6
   CdSph = 2.5*10^-8 * ReSph + 0.15;
end
```

```
  if ReSph>4*10^6
     CdSph = 0.25;
  end

  DragSph = 0.5 * DENW * V^2 * pi/4 * DSph^2 * CdSph; % Drag force caused by
sphere
  VSph = pi * DSph^3 / 6; % Volume of sphere
  FBSph = gammasw * VSph; % N (See Munson book example p.71)
  WSph = g* DEN * VSph; % N

  TVI = FBSph - WSph; % N
  THI = -DragSph; % N

  % Conditions imposed by ballast / float on the acoustic modem.
  tauB = sqrt(TVI^2 + THI^2);
  thetaB = atan(TVI/THI);

  % Calculate the lift and drag coefficients on the acoustic modem.
  % "sign" is the Signum function for MATLAB (theta > 0 => 1, theta = 0 => 0,
  % theta < 0 => -1

  ClS = CoS * (sin(thetaB))^2 * cos(thetaB) * sign(thetaB);

  CdS = CoS * (sin(thetaB))^3 * sign(thetaB) + CfS;

  df_tauS   = ((g * AS * (DENS - DENW) * sin(thetaB)) + (1/2 * DENW * (V^2) * DS
* (CdS * cos(thetaB) - ClS * sin(thetaB)))) * LS;

  tauS = tauB  + df_tauS;

  df_thetaS = ((1 / tauS) * (g * AS * (DENS - DENW) * cos(thetaB) - 1/2 * DENW *
(V^2) * DS * (CdS * sin(thetaB) + ClS * cos(thetaB)))) * LS;

  thetaS = thetaB + df_thetaS;

  TH(1) = tauS * cos(thetaS);
  TV(1) = tauS * sin(thetaS);

  x(1) = 0;
  y(1) = 0;

  % Both x(1) and y(1) provide normalization for the array. The starting
  % point of (0,0) is where the modem connects to the cable.

  % Assume the dimensions of the ballast and modem are negligible for
```

```
   % cable x,y displacement calculations.

   theta(1) = thetaS;
   tau(1) = tauS;

else if Shape == 2 % Streamline body
   ReSB =  V * DSB / Kine;
   LOSB = DSB/2 + LSB + TSB; % Overall length of streamline body

      if  ReSB<10^5
         Cflam = 1.328 / sqrt(ReSB); % Laminar skin friction drag coeffcient (Hoerner
p.2-4)
         Cdwet = Cflam * (1 + ((DSB/LOSB)^1.5)) + (0.11*((DSB/LOSB)^2));
         % This equation is for subcritical Re (10^4 to 10^5). (Hoerner p.6-16 Eqn 24)
         % Assumption that this is viable for Re < 10^5.
      end

      if ReSB>=10^5 && ReSB<=10^9
         Cf = (3.46*log10(ReSB)-5.6)^-2; % (Hoerner p.2-5. Approximation of
Schoenherr
         % line on p.2-6, Figure 5)
         Cdwet = Cf * (1 + 1.5*(DSB/LOSB)^1.5 + 7*(DSB/LOSB)^3); %This equation
is
         % for Re>10^5. (Hoerner p.6-17)
      end

   DragSB = DENW * V^2 * pi/4 * DSB^2 * Cdwet; % Drag force caused by streamline
body
   VSB = (pi/6) * DSB^3 + (pi/4) * DSB^2 * LSB + (pi/12) * DSB^2 * TSB; % (m^3)
   % Approximates volume of streamline body as hemisphere + cylinder + cone.
   FBSB = gammasw * VSB; % N
   WSB = g * DEN * VSB; % N

   TVI = FBSB - WSB; % N
   THI = -DragSB; % N

   % Conditions imposed by ballast / float on the acoustic modem.
   tauB = sqrt(TVI^2 + THI^2);
   thetaB = atan(TVI/THI);

   % Calculate the lift and drag coefficients on the acoustic modem.
   % "sign" is the Signum function for MATLAB (theta > 0 => 1, theta = 0 => 0,
   % theta < 0 => -1
   ClS = CoS * (sin(thetaB))^2 * cos(thetaB) * sign(thetaB);
   CdS = CoS * (sin(thetaB))^3 * sign(thetaB) + CfS;
```

```
   df_tauS   = ((g * AS * (DENS - DENW) * sin(thetaB)) + (1/2 * DENW * (V^2) * DS
* (CdS * cos(thetaB) - ClS * sin(thetaB)))) * LS;
   tauS = tauB  + df_tauS;
   df_thetaS = ((1 / tauS) * (g * AS * (DENS - DENW) * cos(thetaB) - 1/2 * DENW *
(V^2) * DS * (CdS * sin(thetaB) + ClS * cos(thetaB)))) * LS;
   thetaS = thetaB + df_thetaS;

   TH(1) = tauS * cos(thetaS);
   TV(1) = tauS * sin(thetaS);

   x(1) = 0;
   y(1) = 0;
   % Both x(1) and y(1) provide normalization for the array. The starting
   % point of (0,0) is where the modem connects to the cable.

   % Assume the dimensions of the ballast and modem are negligible for
   % cable x, y displacement calculations.

   theta(1) = thetaS;
   tau(1) = tauS;

else if Shape == 3||4; %Initial tensions provided by arbitrary force at end of cable
(substitution for ballast/float)
      % Pode Example 1:   TV(1) = 40495 TH(1) = 23140
      % TV(1) cannot equal zero as arctangent would be undefined.

   TV(1) =  40495;
   TH(1) =  -23140;
   % Because of flow orientation, the arbitrary horizontal force is
   % positive for a towed cable. The horizontal force is negative for a
   % moored cable. When the final results are graphed, the direction of
   % flow will be the same. This does not seem to have an impact on the
   % results.

   tau(1) = sqrt(TV(1)^2 + TH(1)^2);
   theta(1) = atan(TV(1)/TH(1));

   x(1) = 0;
   y(1) = 0;
   % Both x(1) and y(1) provide normalization for the array. The starting
   % point of (0,0) is where the arbitrary forces act on the end of the cable.
   end
   end
end
```

```
% Calculate the cross-sectional area of the cable.
AC = pi * DC * DC / 4; %m^2

for i = 1:n;
% Calculate lift and drag coefficients of the cable.
Cl(i) = Co * (sin(theta(i)))^2 * cos(theta(i)) * sign(theta(i));

Cd(i) = Co * (sin(theta(i)))^3 * sign(theta(i)) + Cf;

% Calculate the new tau and theta coefficients for each successive segment.
df_tau(i) = ((g * AC * (DENC - DENW) * sin(theta(i))) + (1/2 * DENW * (V^2) * DC *
(Cd(i) * cos(theta(i)) - Cl(i) * sin(theta(i))))) * ds;

tau(i+1) = tau(i)  + df_tau(i);

df_theta(i) = ((1 / tau(i+1)) * (g * AC * (DENC - DENW) * cos(theta(i)) - 1/2 * DENW *
(V^2) * DC * (Cd(i) * sin(theta(i)) + Cl(i) * cos(theta(i))))) * ds;

theta(i+1) = theta(i) + df_theta(i);

% Calculate the x and y position for each segment.
x(i+1) = cos(theta(i)) * ds + x(i);

y(i+1) = sin(theta(i)) * ds + y(i);

% Calculate the new horizontal and vertical components of tension.
TH(i) = tau(i) * cos(theta(i));

TV(i) = tau(i) * sin(theta(i));
end

tauN = sqrt(TV.^2 + TH.^2); % Total cable tension in N
taulb = tauN * 0.22482; % Total cable tension in lbf

thetarad = atan2(TV,TH); % Cable angle per segment in radians.

% Corrections so data is properly graphed for each case.
% Equivalency is:
% Towed cable is the same as Shape = 3 is the same as Density = 2.
% Moored cable is the same as Shape = 4 is the same as Density = 1.

if Shape == 3 % (0,0) is where cable connects to buoy on seasurface.
    e = y(n+1);
    y = y-e;
    f = x(n+1);
```

```
    x = x-f;
    thetadeg = rad2deg(thetarad) + 180;
    figure(1)
    plot(x,y,'r','LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    title('2-D Position of Towed Cable')
    xlabel ('Horizontal Displacement (m)');
    ylabel ('Depth Below Seasurface (m)');

else if Shape == 4  % assumes (0,0) is where cable connects to ground.
    e = y(n+1);
    y = y-e;
    f = x(n+1);
    x = x-f;
    thetadeg = rad2deg(thetarad) + 180;
    figure(1)
    plot(x,y,'r','LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    title('2-D Position of Moored Cable')
    xlabel ('Horizontal Displacement (m)');
    ylabel ('Height Above Seafloor (m)');

else if Density == 1 % assumes (0,0) is where cable connects to ground.
    e = y(n+1);
    y = y-e;
    f = x(n+1);
    x = x-f;
    thetadeg = rad2deg(thetarad) + 180;
    figure(1)
    plot(x,y,'r','LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    title('2-D Position of Moored Cable')
    xlabel ('Horizontal Displacement (m)');
    ylabel ('Height Above Seafloor (m)');

else if Density == 2 % (0,0) is where cable connects to buoy on seasurface.
    e = y(n+1);
    y = y-e;
    f = x(n+1);
    x = x-f;
    thetadeg = rad2deg(thetarad) + 180;
    figure(1)
    plot(x,y,'k', 'LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    hold on
    title('2-D Position of Towed Cable')
    xlabel ('Horizontal Displacement (m)');
    ylabel ('Depth Below Seasurface (m)');
    end
```

```
        end
        end
end

%axis square
grid on
hold on

% thetadeg corresponds to the angle relative to the horizontal. The first
% angle is where the cable connects to the ballast/float.
% tauN is the tension in the cable. The first tension corresponds to where
% the cable connects to the ballast/float.

% Comment out lines 410-425 when evaluating multiple cables.
% When final cable is being evaluated, uncomment lines 410-425 to add
% seafloor or seasurface. Otherwise, only one cable graph will show with
% the seasurface and seafloor. The seasurface/seafloor are used a a
% reference point to show the user that the cable will violate a boundary.
% MATLAB does not change its calculations if the cable violates a boundary.

z = -L:L/8; % Sets limits for seafloor and seasurface horizontal boundaries.
% Default set to 1.25 cable scope with more emphasis on the left side of
% (0,0) as current flows from right to left.

if Shape == 3
        plot (z,0,'b','LineWidth', 2,'Marker', '^', 'MarkerSize', 6);
    else if Shape == 4
        plot (z,0,'k','LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    else if Density == 1
        plot (z,0,'k','LineWidth', 2,'Marker', '.', 'MarkerSize', 2);
    else if Density == 2
        plot (z,0,'b','LineWidth', 2,'Marker', '^', 'MarkerSize', 6);
    end
    end
    end
end

legend Nitronic50B Spectra1000 Seafloor %change legend as necessary
(seafloor/seasurface is always last)

% legend 100m 10m 1m Seafloor
% legend 17.46mm 15.88mm 14.29mm 12.70mm Seafloor
% legend Sphere StreamlineBody Seafloor
% legend 0.0kt 0.5kt 1.0kt 1.5kt 2.0kt 2.5kt 3.0kt Seafloor
% legend Nitronic50B Spectra1000 Seafloor
```

APPENDIX B. SYNTACTIC FOAM SPECIFICATIONS

BZ Grade

High Performance Syntactic

Engineered Syntactic Systems

Deep Water Foam (Bathypelagic Zone)

107 Frank Mossberg Drive
Attleboro, MA 02703
TEL (508) 226 - 3907 FAX (508) 226 – 3902
tech@esyntactic.com www.esyntactic.com

Overview

Syntactic foams are a unique combination of hollow spheres, a resin matrix, and other additives. When combined and processed properly, the constituents form a lightweight homogeneous material having high compressive and hydrostatic strengths. This yields a product able to withstand the high hydrostatic pressures experienced by today's manned and unmanned subsea vehicles.

The BZ Grade of material is specially engineered, high performance syntactics capable of operating within much of the Bathypelagic Zone (4,000 meters or 13,100 feet). Due to the nature of the syntactic constituent materials, the BZ Grade is available in a range of densities and strengths. The product is cast in block, sheet or rod form and has isotropic properties. It may be cut or machined to any size or shape to consistent buoyancy at depth.

Each block is cast as a single unit, but may be cut to fit the application requirement. Blocks or trimmed parts may also be bonded together to form a larger structure. Standard block size is 6 inch x 12 inch x12 inch, but custom sizes and shapes, including round stock, are available.

Properties

Properties provided below are typical for the cast block:

Product	Density lb/ft^3 (g/cc)	Service Pressure psi (Bar)	Service Depth feet (meters)	Compressive Strength psi (Mpa)	Compressive Modulus ksi (Gpa)	Hydrostatic Crush psi (Bar)	Weight gain 24 hours @ depth
BZ - 24	24 ± 2 (0.39 ± .03)	3,200 (221)	7,250 (2,200)	2,900 (20.0)	170 (1.17)	4,500 (310)	3 % Max
BZ - 26	26 ± 2 (0.42 ± .03)	4,300 (296)	9,750 (2,980)	3,950 (27.2)	180 (1.24)	5,350 (370)	3 % Max
BZ – 28	28 ± 2 (0.45 ± .03)	5,500 (379)	12,500 (3,810)	4,880 (33.6)	210 (1.45)	6,200 (427)	3 % Max
BZ – 30	30 ± 2 (0.48 ± .03)	6,000 (414)	13,600 (4,150)	5,200 (35.9)	240 (1.65)	7,000 (482)	3 % Max

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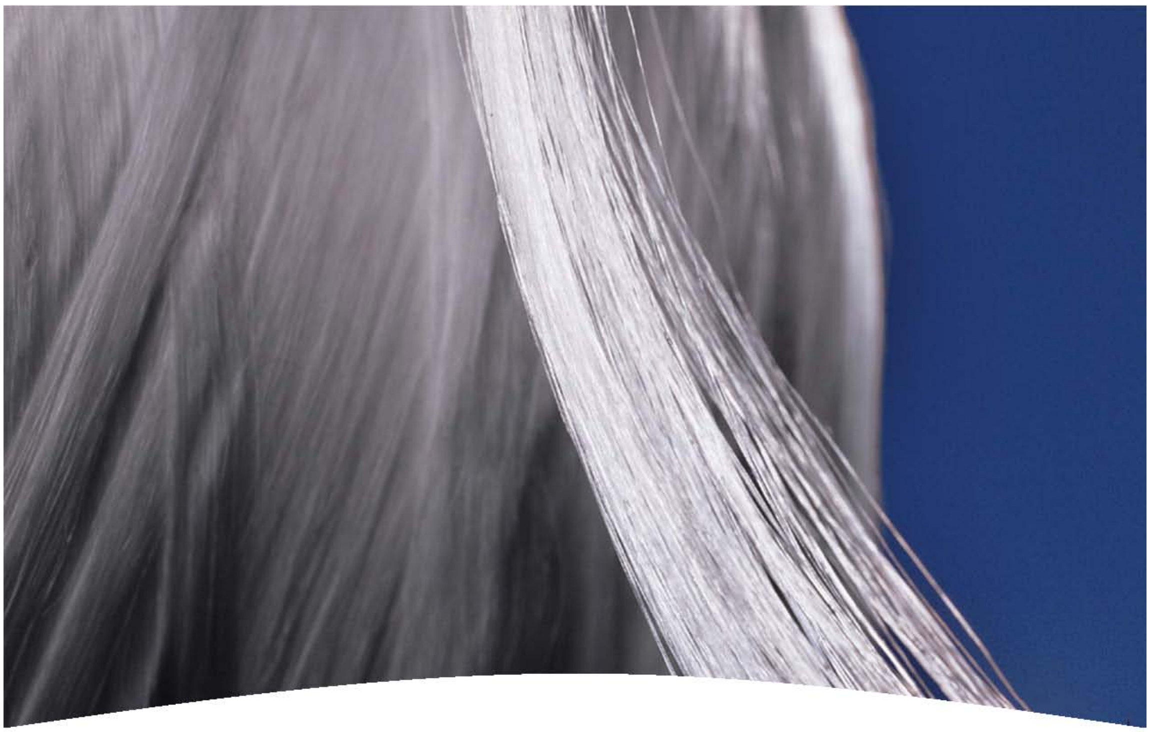
APPENDIX C. SPECTRA FIBER SPECIFICATIONS

Honeywell



Honeywell Spectra® fiber 1000
high-strength, light-weight polyethylene fiber

Product Information Sheet

SPECTRA® fiber 1000
high-strength, light-weight polyethylene fiber

PRODUCT DESCRIPTION: Spectra fiber 1000, the second in a series of Spectra fibers, was developed to meet customers' needs for increased performance. It is available in a multitude of deniers for use in a wide range of applications.

This extended-chain polyethylene fiber has one of the highest strength-to-weight ratios of any man-made fiber. Spectra fiber 1000 has a tenacity 15 to 20 percent higher than that of Spectra fiber 900. Spectra fiber is, pound for pound, 15 times stronger than steel, more durable than polyester and has a specific strength that is up to 40 percent greater than that of aramid fiber. Specific performance is dependent upon denier and filament count.

Applications:
- Police and military ballistic vests and helmets
- Composite armor for vehicles and aircraft
- Marine lines and commercial fishing nets
- Industrial cordage and slings
- Sailcloth, fishing line and other sporting equipment
- Cut-protection products

Product Benefits:
- Light enough to float (0.97 g/cc specific gravity)
- High resistance to chemicals, water and ultraviolet light
- Excellent vibration damping
- Highly resistant to flex fatigue
- Low coefficient of friction
- Good resistance to abrasion
- Low dielectric constant makes it virtually transparent to radar

PHYSICAL PROPERTIES							
(Nominal)	Spectra® fiber 1000						
Weight/Unit Length (Denier) (Decitex)	215 239	275 306	375 417	435 483	650 722	1300 1444	2600 2888
Ultimate Tensile Strength (g/den) (Gpa)	38 3.25	36 3.08	35 3.00	34.5 2.95	36 3.08	35 3.00	34 2.91
Breaking Strength (lbs.)	18.0	22.0	29.0	33.0	52	100	195
Modulus (g/den) (Gpa)	1320 113	1320 113	1200 103	1180 101	1175 101	1150 98	1135 97
Elongation (%)	2.9	3.1	3.1	3.2	3.5	3.3	3.5
Density (g/cc) (lbs/in^3)	0.97 0.035	0.97 0.035	0.97 0.035	0.97 0.035	0.97 0.035	0.97 0.035	0.97 0.035
Filament/tow	60	60	60	120	120	240	480
Filament (dpf)	3.6	4.6	6.3	3.6	5.4	5.4	5.4

For more information:
Honeywell Specialty Materials
101 Columbia Road
Morristown NJ, 07962
Toll Free: 1-800-695-5969
Europe: +32 16 39 12 19
Asia: +86 21 2894 2000
www.honeywell.com/spectra

Honeywell

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20. Harry Cox
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21. Edward Johnson
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